A Power-Aware Approach to Processing Payload Design

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Abstract

An intelligent payload concept is described that processes RF lightning signal data onboard the spacecraft in a power-aware manner while remaining sensitive to the mission goals. This resource-critical technology of onboard processing is addressed through the concept of Algorithm Power Modulation (APM). A straightforward APM decision procedure is provided as an example of implementing APM for this application.

1. INTRODUCTION

Our objective is to maximize capability and performance of remote-sensing satellites through smarter use of processing resources. With a limited power budget, traditional power management strategies make significant onboard processing impractical. Conventional spacecraft architectures only collect raw data, leaving processing tasks to be performed on the ground. By enabling onboard processing, it is hoped to *quickly provide accurately processed, field-usable data* to the end-user. However, in this resource critical problem, a smarter distribution of power resources is essential.

We are developing a power management design paradigm for intelligent, next-generation processing payload systems through the unique concept of Algorithm Power Modulation (APM). With APM, a spacecraft payload processor can operate at multiple levels of power consumption in a power-aware manner while remaining sensitive to the mission tasks. Through judicious selection of the processing algorithms, data can still be processed onboard at some level of accuracy even during periods of low power availability.

In this paper, we describe a power-aware processing payload concept that utilizes APM to process simulated orbital lightning signal data. This application is focused on improving detection capability through accurate, post-trigger processing. A straightforward APM decision procedure for this application is discussed.

2. BACKGROUND AND MOTIVATION

Advances in electronics technology have produced multiple modes of processing operation. A processor can operate in different modes at varying levels of power consumption; for example, the IBM PPC750 266MHz processor has 5 typical modes of operation that range from 30mW to 5.7W [1]. Most notably, multiple operational modes are commonplace in ordinary laptop computing to conserve battery power while disconnected from an external power outlet.

A recent area of power research, sponsored by the Defense Advanced Projects Agency (DARPA) Power Aware Computing/Communications (PAC/C) program, is focused on developing intelligent, power-aware systems [2]. This research is based on the premise that systems aware of their own power usage can make better use of the available power resources. A system aware of its power consumption can dynamically adjust processing frequency, voltage, and workload tasks to change the operational mode.

Although intelligent power management has been a cutting-edge research topic in recent years for ground-based, mobile computing systems, it still remains largely unexplored for spacecraft applications. Existing satellite power management strategies are not flexible enough to take full advantage of these emerging processing technologies.

Spacecraft power is traditionally handled onboard using static, non-intelligent designs. The conventional strategy is a basic binary approach: a subsystem is either on or off. Simplified, onboard Boolean logic protects against power system faults. During severe power-constrained or unexpected conditions, such as eclipse or partial solar panel failure, non-critical subsystems may be turned off altogether.

Under such circumstances, payload subsystems are typically the first to be turned off. Although essential to the mission objective, the payload is not necessary for spacecraft survival. This operational paradigm can result in a loss of vital data at a crucial moment.

Additionally, payload instruments are providing significant increases in resolution while at the same time generating larger amounts of raw data. The power and latency costs in transmitting and processing this bulk data to the end-user can be significant. Currently, delays of days to weeks can be experienced before the data is received by the appropriate agency, processed into a human-usable format, and finally transmitted to the end-user.

Enabling onboard processing can improve detection capability, enhance satellite response performance, and increase data quality transmitted to the ground. Onboard, layered processing techniques can extract or flag significant features in the raw data sets to speed up and supplement a ground-based analysis.

However, the traditional satellite power management paradigm does not utilize multiple modes of hardware operation that can maximize spacecraft capability and performance. Our research focuses on developing a processing payload system that executes signal processing tasks *in-situ* based on the available resources while remaining sensitive to the mission objectives.

LA-UR-02-7779

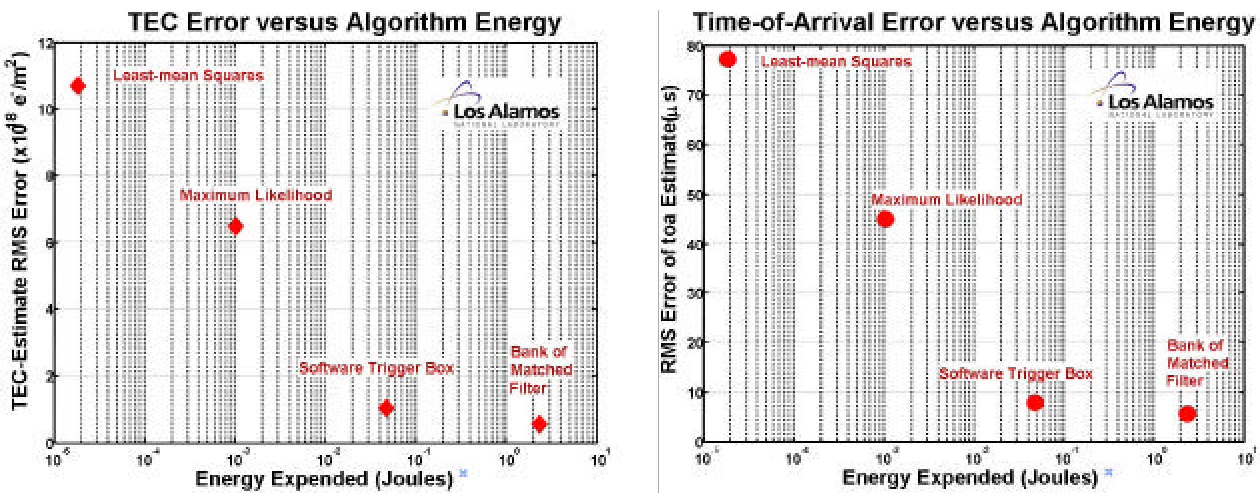

Figure 1. Algorithm Parameter Estimation Performance

3. A POWER-AWARE, PROCESSING PAYLOAD CONCEPT

We have chosen an application similar to the Fast On-Orbit Recording of Transient Events (FORTÉ) satellite mission to demonstrate APM. A primary objective of FORTÉ is to detect the Radio-Frequency (RF) signal of lightning events in the Earth's atmosphere [3]. Orbital monitoring of global lightning conditions can help to provide severe storm warnings[1]. The speed at which a severe storm warning can be issued is related to how accurately the lightning signals are detected and how quickly the data is returned to the ground and analyzed.

As received on-orbit, the RF lightning signal is a "chirp" waveform amidst a noise of anthropogenic signals. The chirp signal is a result of the frequency dispersion experienced during propagation through the ionosphere. An analog trigger box provides multiple channels of sub-band filters that attempt to detect the presence of a lightning event. FORTÉ does not have the capability to process this data onboard and, hence, stores only raw data for downlink. The existing RF payload can miss true events through improper setting of the sub-band filter detection thresholds. It is envisioned that the onboard processing techniques enabled by APM will help to minimize missed events and reduce the probability of false alarms in the next-generation FORTÉ RF payload.

Sponsored by the DARPA PAC/C research program, we have targeted the Power Aware Multiprocessor Architecture (PAMA) hardware to demonstrate and evaluate APM technology with this FORTÉ application. PAMA is a 4-node, multiprocessor board under development by the Information Sciences Institute [4].

In [5], we first summarized this project and described 4 signal-processing algorithms that would process the simulated RF data. The 4 algorithms include a Least-Mean-Squares (LMS), Maximum Likelihood (ML), Software Trigger (ST)[2], and a bank of Matched Filters (MF). These algorithms are used to estimate the primary parameters of interest from the chirp signal, namely, the Total Electron Content (TEC) and Time-Of-Arrival (TOA).

An algorithm power experiment was performed on a PPC750 266MHz test-bench provided by the Jet Propulsion Laboratory as part of the PAC/C effort. The result was a 10^6 order of magnitude difference in power consumption (energy)[3] between the 4 algorithms.

These 4 algorithms have since been exercised via Monte Carlo testing with the simulated data. Using the Root-Mean-Squared (RMS) error as a metric of performance, these performance values were correlated with the energy measurements. The algorithms outline a decaying exponential profile with an increase in energy expended (see Figure 1).

The selected algorithms can be used for a post-trigger processing analysis to readjust detector threshold settings based on the incoming signal data. The Receiver Operator Characteristic (ROC) curve defines the detection relationship between the probabilities of false alarms vs. detection (of a true event). Once the threshold settings are selected, the detector ROC operating point is fixed: a defined probability of false alarms must be accepted for a desired probability of detection. Through onboard, post-trigger processing of the incoming data, the thresholds can be adjusted to reduce the probability of false alarms (see Figure 2). Concurrent research is being performed to quantitatively evaluate this post-trigger processing technique [6].

[1] The monitoring of lightning is of particular interest to many weather service agencies. Advance notice of severe storm conditions is important to protect against loss of life and property.

[2] The ST performs multiple, short FFTs on the signal data.

[3] In our terminology for this paper, "power consumption" implies a time duration over which the power is consumed, not an instantaneous measure, e.g., Watts. Power consumed over time is expressed as energy, e.g., Joules.

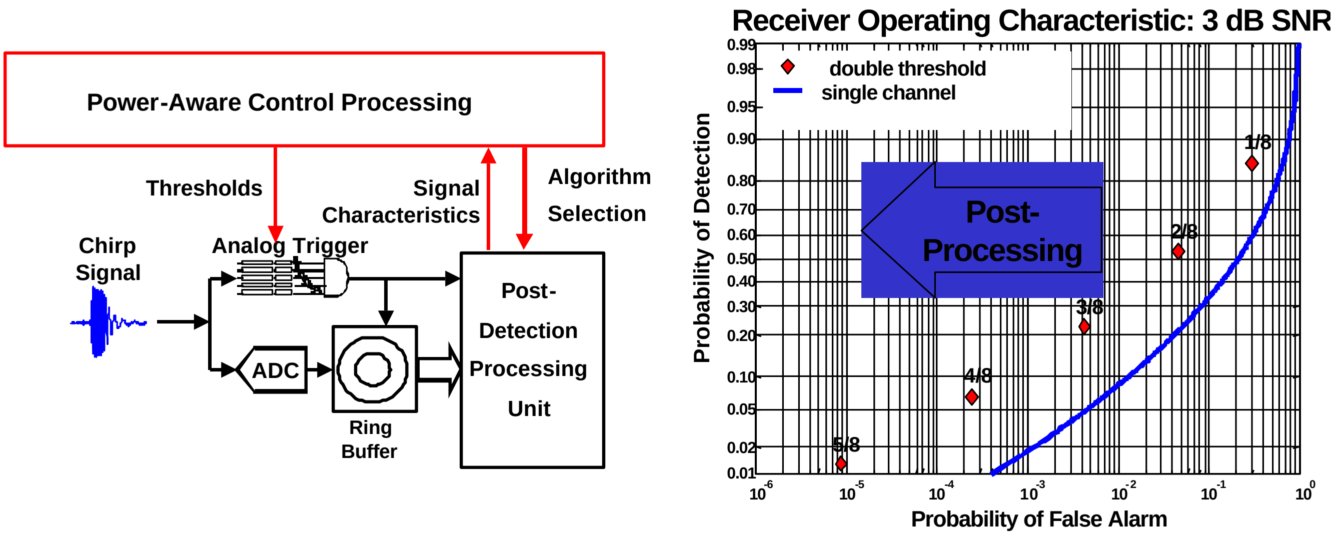

Figure 2. Power-Aware, Post-Trigger Processing Threshold Adjustment

The heart of APM is a decision process that determines which signal-processing algorithm to execute based on the available resources. Each algorithm has an associated cost of energy and accuracy to execute. Combined with the available power and the incoming event rate, these algorithm performance parameters define the decision trade-space.

4. AN APM DECISION EXAMPLE

As an example, we will examine a straightforward decision procedure that implements APM for a simplified model of our application. In this exercise, we assume a single processor, similar to that used in the JPL power experiment. This processor can execute the chosen LMS, ML, ST, and MF algorithms as described in the previous section with the given performance illustrated in Figure 1. For simplification, we will neglect the detection threshold problem explored in [6], and instead focus on accurate parameter estimation.

We adopt the operational perspective of running one algorithm over a specified time interval T. The number of times an algorithm i, with execution time t^i, can execute in period T is denoted as n^i.

$$n^i = \frac{T}{t^i} \qquad (1)$$

Note that we are assuming a constant execution of algorithm i throughout time period T.

The power is constrained by the limitation of the spacecraft power source. Exceeding the available capacity can result in shutting off the payload. This capacity changes with time over the orbit. If we divide up the orbit into T periods, C denotes the capacity for this period. Equation 2 illustrates the power constraint that must be satisfied for algorithm i, with instantaneous power dissipation p^i.

$$p^i T \le C \qquad (2)$$

An additional constraint is determined from the incoming event rate. The number of lightning events occurring in period T is dependent upon an average rate of events R_{avg}. If no events are to be lost, the chosen algorithm must satisfy the following constraint:

$$n^i \ge R_{avg} T \qquad (3)$$

In other words, the number of times algorithm i executes must be greater or equal to the number of events. It is implicitly assumed that the processor must process each event at least once and be ready to process the event as it occurs.

The objective is to determine algorithm i that has the minimum associated error, e^i, subjected to the constraints given by equations 2 and 3. A statement of this problem is illustrated by the following for k total algorithms:

Given R_{avg}, T, C, and p^i for $i = 1, 2, 3, \ldots, k$

Determine $\min\{e^i\}$

Satisfying $T \le \min\left\{\frac{n^i}{R_{avg}}, \frac{C}{p^i}\right\}$

If C and R_{avg} remain fairly constant over the orbit, the solution is straightforward. In such a case, it is a simple matter to select *apriori* which algorithm is appropriate. Since there are only 4 algorithms, an exhaustive search method can be easily implemented over the specified T intervals. This could be construed as a traditional, ground-based operational approach: *predict the given parameters and schedule the appropriate algorithm over the specified time period*. If an unpredicted, deleterious change in power occurs, the onboard logic will shut down the payload. Operators will then command a system restart when possible.

The cost in this approach is in the time taken for operator response. There are associated communication delays based on the orbit and ground station locations. Often, ground operators issue new commands based on information delayed by a few orbits. When the payload is shut down, the number of events missed could be significant.

Additionally, both C and R_{avg} do not remain constant for this application. FORTÉ itself experiences a wide variation from a maximum peak of 325W [3] to an orbital daily average of 55W [7]. Experiments in optical lightning observations report widely varying global flash rates between 40 flashes/sec. to 120 flashes/sec. [8], [9], [10]. The lightning event rate[4], as observed by FORTÉ, has a median of 2 events/flash and a maximum of 20 events/flash[5].

It is evident that, due to the variable nature of the power and event rate conditions, the onboard decision process must *measure the available power and event rate, and then select the algorithm with the least amount of error that satisfies these conditions*.

5. CONCLUSIONS

We have described a processing payload concept utilizing the idea of Algorithm Power Modulation. The payload is modeled after the FORTÉ satellite mission of detecting lightning events in the Earth's atmosphere. APM can be used to enable onboard processing of these frequency-dispersed signals. Detector threshold settings can then be adjusted based on the processed signals to improve detection performance. This is accomplished by operating in multiple modes of operation through selection of the appropriate signal-processing algorithm. Each algorithm has an associated level of parameter estimation accuracy and power consumption.

As an initial exploration, a simplified decision procedure to the APM concept is presented. This procedure is developed from the perspective of operating one algorithm for specified time intervals of the spacecraft's orbit. Two primary constraints were illustrated based on the available power capacity and the desired mission objective of not missing any events. Due to the highly variable nature of the power and event rate conditions, it is concluded that the system should measure the available power and event rate, and then select the algorithm with the least amount of error that satisfies these constraints.

It is hoped that our work will lead to enabling onboard processing in remote-sensing satellites to improve detection capability, enhance satellite response performance, and increase data quality transmitted to the ground. Through APM, we aim to manage onboard processing resources in a more intelligent manner than is currently employed in conventional designs.

[4] A single optical lightning flash may consist of multiple events observable by examining the RF spectrum.

[5] These event rates were obtained in conversation with Dr. Tracy Light, LANL NIS-1. Dr. Light participates in analyzing FORTÉ lightning signal data.

6. ACKNOWLEDGEMENTS

This effort has been sponsored by DARPA through the Air Force Research Laboratory, USAF, under agreement number F30602-00-2-0548. We are grateful to Dr. Tracy Light, LANL NIS-1 for her insight into lightning event rates and to Dr. Simon Perkins, LANL NIS-2 for his operational APM perspective.

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